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Design Concept and Testing of an In-Bundle Gamma Densitometer for Subchannel Void Fraction Measurements in the THTF Electrically Heated Rod Bundle

D. K. Felde

Prepared for the U.S. Nuclear Regulatory Commission
Office of Nuclear Regulatory Research
Under Interagency Agreements DOE 40-551-75 and 40-552-75

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Engineering Technology Division

DESIGN CONCEPT AND TESTING OF AN IN-BUNDLE GAMMA DENSITOMETER FOR SUBCHANNEL VOID FRACTION MEASUREMENTS IN THE THTF ELECTRICALLY HEATED ROD BUNDLE

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Prepared by the
OAK RIDGE NATIONAL LABORATORY
Oak Ridge, Tennessee 37830
operated by
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ABSTRACT

A design concept is presented for an in-bundle gamma densitometer system for measurement of subchannel average fluid density and void fraction in rod or tube bundles. This report describes (1) the application of the design concept to the Thermal-Hydraulic Test Facility (THTF) electrically heated rod bundle and (2) results from tests conducted in the THTF.

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1. INTRODUCTION

An in-bundle gamma densitometer system was designed to measure subchannel average fluid density and void fraction in the Thermal-Hydraulic Test Facility (THTF) electrically heated rod bundle. This report describes the basic design concept of the system and the results from initial tests in the THTF.

Oak Ridge National Laboratory (ORNL) has conducted a series of experiments in the THTF as part of the Pressurized-Water Reactor (PWR) Blowdown Heat Transfer (BDHT) Separate Effects Program. The primary purpose of the program is to produce rod bundle data that can be used to provide insight into the thermal-hydraulic behavior of light-water reactor cores during hypothetical accidents. To this extent, measurement of in-bundle fluid conditions such as void fraction or average fluid density is valuable for in-bundle flow characterization and thermal-hydraulic code validation.

A diagram of the THTF in its standard configuration is shown in Fig. 1. The test section contains an electrically heated fuel rod simulator (FRS) bundle in an 8 x 8 array typical of late-generation 17 x 17 PWR bundles. The FRSs have a full 3.66-m (12-ft) heated length with a flat power profile.[1] The system is capable of operating at pressures and temperatures typical of PWRs.

Both transient and steady-state tests have been run at the THTF. Transient tests are initiated by rupturing the system pressure boundaries at the test section inlet and/or outlet piping. Initial system pressure and test section outlet fluid temperatures are typically 15 MPa (2250 psi) and 593 K (608°F), respectively. At blowdown, the system undergoes an initial subcooled decompression followed by a voiding of the system, which is controlled primarily by critical flow orifices at the rupture sites and by power applied to the electrically heated rod bundle in the test section.

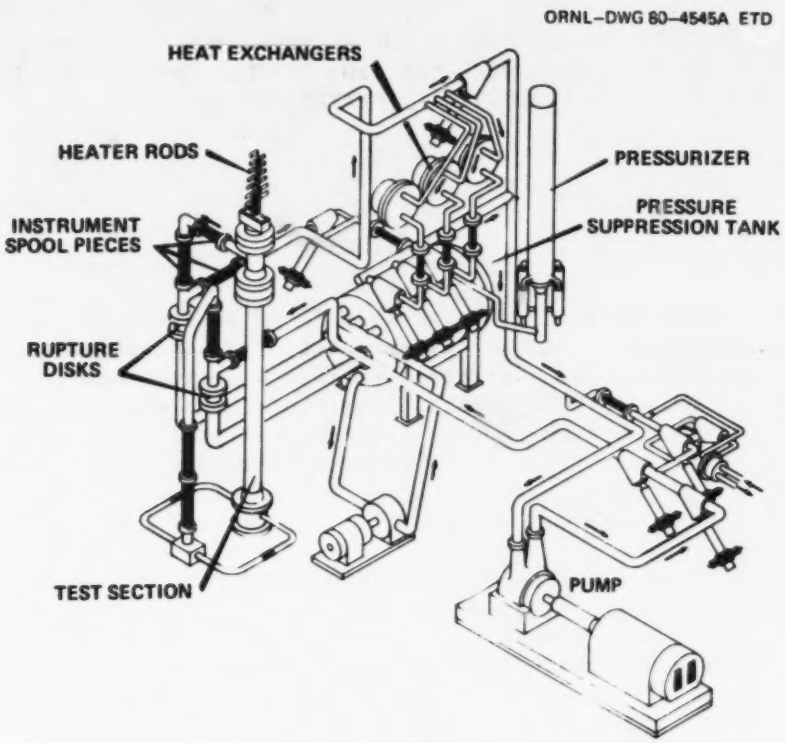

Fig. 1. THTF in standard configuration.

Steady-state tests are operated by setting the desired inlet mass flow rate and then increasing power and decreasing the system mass inventory until the desired bundle conditions are reached.

The in-bundle densitometer uses a low-energy gamma source and an ion chamber positioned in two of the instrumented rod positions of the THTF bundle 3. A schematic of the rod bundle cross section is shown in Fig. 2. A line-of-sight path that crosses two subchannels exists between unheated instrument rod positions 36 and 46. The design concept, then, is the determination of in-bundle void fraction by measurement of the variation in the attenuation of the gamma source across the subchannel path length.

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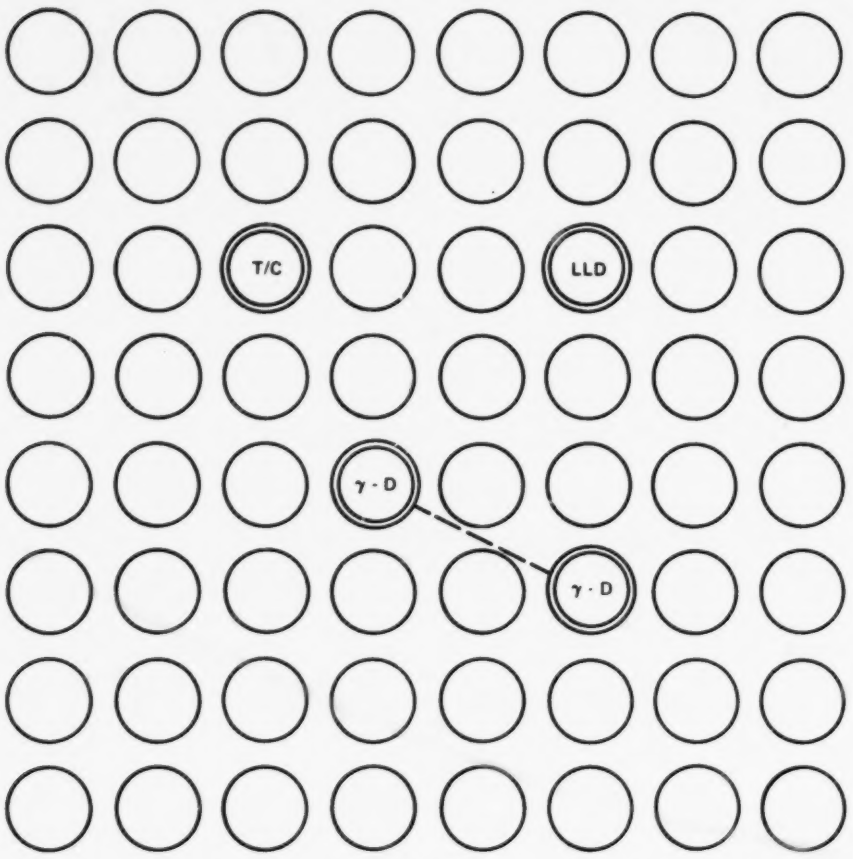

FUEL ROD SIMULATORS

INSTRUMENT RODS

T/C - THERMOCOUPLE ARRAY ROD

LLD - INEL LIQUID LEVEL DETECTOR

γ - D - IN-BUNDLE GAMMA DENSITOMETERS

Fig. 2. Cross section of THTF rod bundle.

2. SYSTEM DESCRIPTION

2.1 Design Description

The actual system is comprised of two 10-Ci gadolinium oxide (Gd_2O_3) (^{153}Gd) sources, two ion chambers with associated electronics, and a motor drive system for remote positioning and recording of the measurement axial locations. The conceptual design of the complete system is shown in Fig. 3. The source and detector assemblies are loaded from the top of the bundle into the hollow instrument rods. The instrument rods, which are 1.018-cm-OD (0.401-in.) by 0.101-cm-wall (0.040-in.) stainless steel tubing, form the boundary between system pressure and atmosphere. Because seals are not required on the source and detector assemblies themselves, installation and removal is a fairly simple procedure.

A detail of the source-detector radial geometry is shown in Fig. 4 and an axial profile in Fig. 5. An annular source design is employed that allows placement of two axially located source-detector systems using only two instrument rod positions. For the instrument rod wherein the source is located above the ion chamber detector, the ion chamber signal cable passes through the upper source support tube and out of the instrument rod tube.

The active source is 10 Ci of Gd_2O_3 (100-keV gammas of ^{153}Gd) encapsulated in a stainless steel semiannulus. The semiannulus is attached to the source support tube, a 3/16- by 0.020-in.-wall stainless steel tube. This support tube allows passage of the ion chamber cable. The source assembly has a nominal 0.686-cm (0.270-in.) outer diameter. The active source is nominally 0.079 cm (0.031 in.) thick with an active length of 3.81 cm (1.5 in.).

The ion chamber is a special modification of a Reuter-Stokes in-core flux probe. It has a 0.635-cm (0.250-in.) outer diameter with a 5.08-cm (2-in.) sensitive length and a fill gas of 20 atm of xenon. The ion chamber cable is nominal 0.317-cm-OD (1/8-in.) triax cable. The electronics are ORNL-designed.

A brief description of the ion chamber operation is presented to provide a basis for later discussion on temperature-effect problems encountered during testing. Fig. 6 is a simplified diagram of the ion chamber and triax cable electrical configuration. The ion chamber operates with an applied voltage of 67.5 V between the center signal electrode and the grounded outer-sheath electrode. The applied voltage across the ion chamber generates a current proportional to the interaction rate of gammas as the charges produced by the ionizing interactions are collected at the electrodes. The triax cable connects the ion chamber to the electrometer front end of the ORNL electronics, where the current is measured on the center signal wire. Measured currents on the center signal wire at the electrometer may also include leakage currents across the insulators in both the ion chamber and triax cable.

At low temperatures the insulator resistance is very high, and the leakage current across the insulators is small as compared with the ionization-generated currents. As temperatures increase and the insulator resistance decreases, however, the leakage current may become a significant portion of the total current measured on the signal wire. The triax

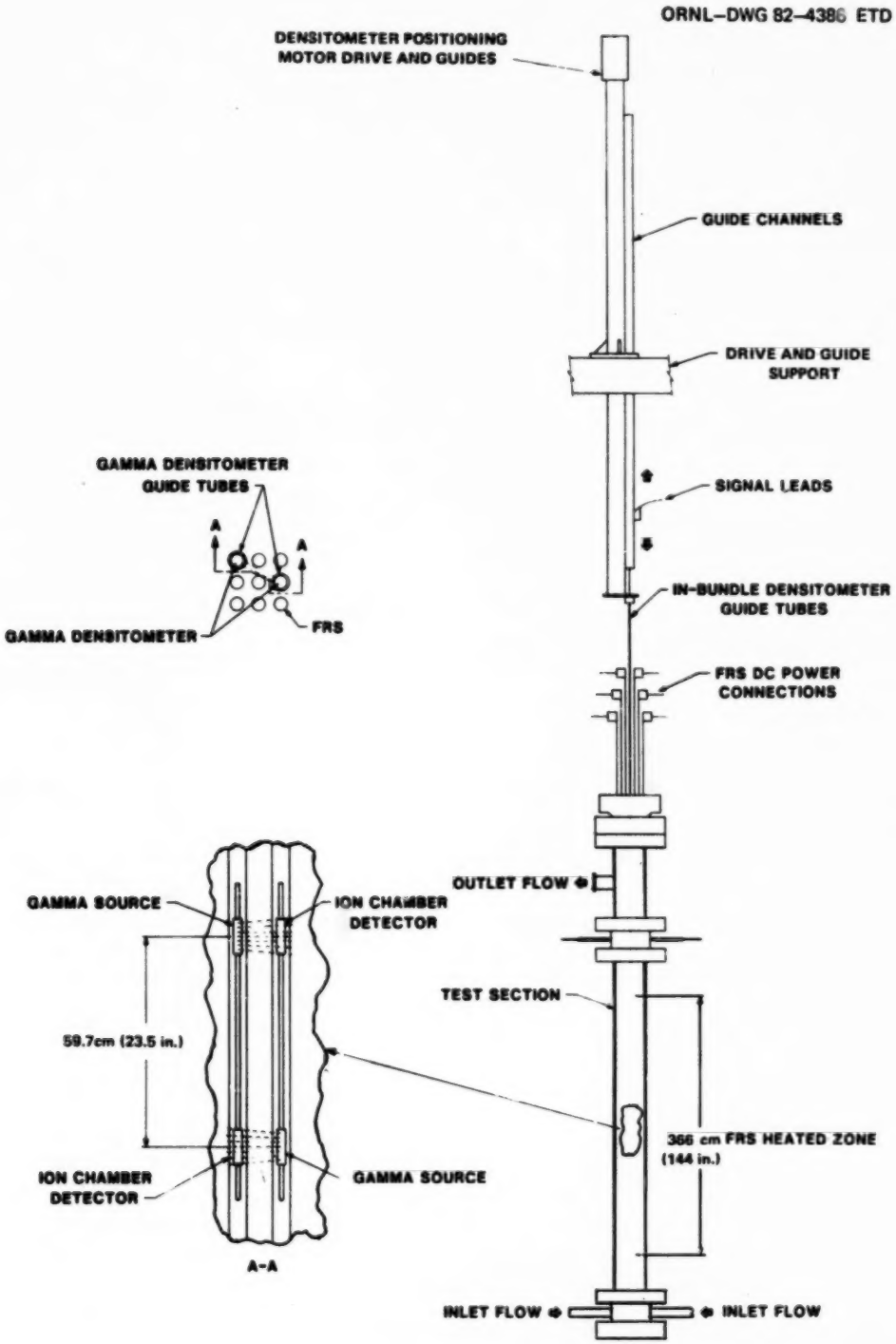

Fig. 3. Schematic of THTF in-bundle gamma densitometer design concept.

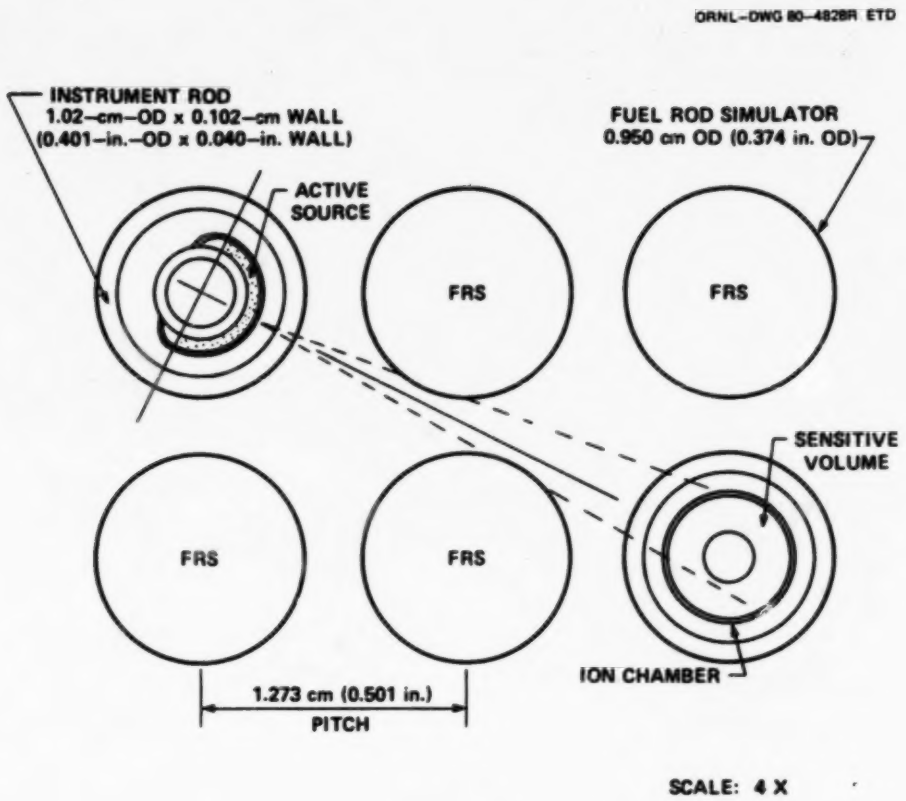

Fig. 4. Detail of THTF in-bundle densitometer source-detector radial geometry.

cable is operated with a guard voltage on the inner conductor sheath to improve the high-temperature capabilities of the cable. The guard voltage follows the applied signal voltage, thus reducing the potential difference seen by the center signal wire. Leakage currents from the inner conductor sheath to the grounded outer sheath are not measured on the center signal wire. The leakage currents included in the measured signal in this case are driven by the potential between the applied signal voltage and the guard voltage.

The ion chamber itself, however, is not fully guarded. It is basically a coaxial design with a ceramic insulator between the center signal electrode and the outer sheath at the ends of the ion chamber. Measured leakage currents in this case are driven by the entire applied voltage across the two electrodes. A design improvement that would extend the temperature range of the densitometer system would be a fully guarded ion chamber design. An ion chamber of this type that would meet the size limitations imposed was not available within the THTF test schedule limitations.

The motor drive system is shown in Fig. 3. The motor drive allows remote positioning of the two measurement sites. A potentiometer included

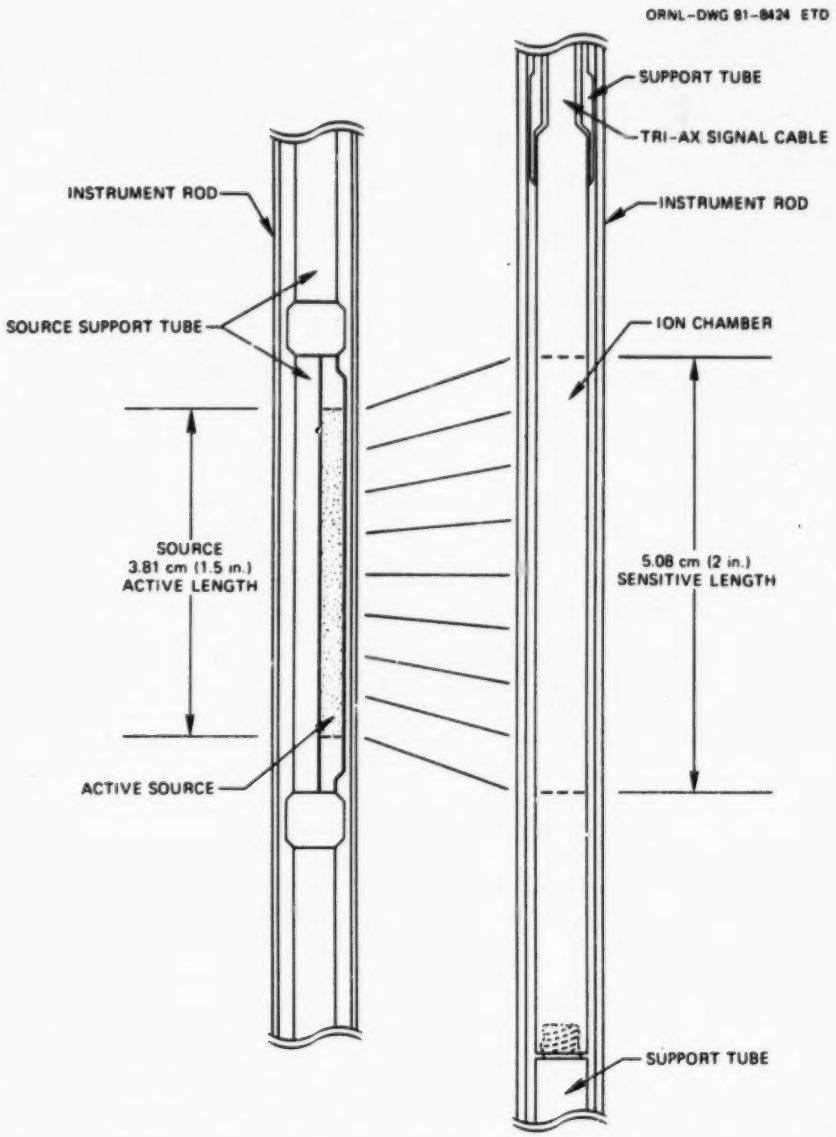

Fig. 5. Cutaway view of source-detector axial geometry—side view.

in the system provides an accurate determination of the location of the densitometers in the bundle. The two measurement sites have a fixed separation distance of 59.7 cm (23.5 in.), which is equivalent to the separation distance between primary FRS thermocouple levels in the bundle. The motor drive also permits operation of the densitometer in the scanning mode, although calibration becomes much more difficult in that case.

Once installed in the bundle, additional shielding of the sources for safety reasons is not required. The shroud box wall surrounding the rod

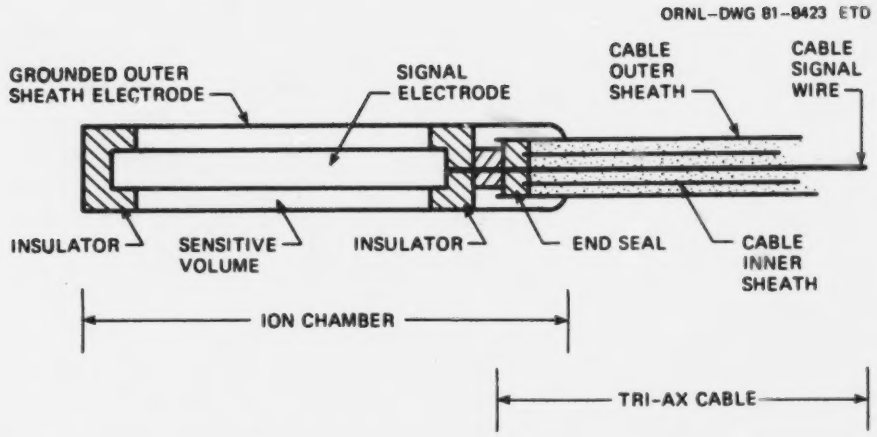

Fig. 6. Simplified diagram of coaxial ion chamber and triax cable design.

bundle and the outer test section barrel provide adequate shielding of the low-energy gammas.

2.2 Calibration

The calibration of the densitometer assumes an exponential attenuation of source gammas. This assumption is generally valid for systems with good geometry[2] characterized by a monoenergetic, collimated beam of small solid angle and a "thin" absorber. Generally, real systems only approach the ideal case, and this is true of the design presented here. The in-bundle geometry imposes somewhat severe constraints on size and component design. The ^{153}Gd source does produce another lower-energy gamma (~40 keV); however, self-shielding effects result in an essentially monoenergetic 100-keV source. The FRSs between the source and detector along the path length define the beam collimation. Although the FRSs are not perfect absorbers, they should provide fairly good collimation, especially as the beam deviates from the desired path length and the absorber thickness seen by the beam increases. The thin absorber requirement implies that a single scattering event should remove the photon completely from the beam. The mean range of the photons[3] is defined as

$$\frac{\int_0^\infty x e^{-\mu\rho x} dx}{\int_0^\infty e^{-\mu\rho x} dx} = \frac{1}{\mu\rho} . \qquad (1)$$

The value of $1/\mu\rho$ for subcooled water of density 0.72 g/cm^3 (45 lb$_m$/ft^3) is 8.1 cm (3.2 in.). This is approximately four times as long as the

nominal subchannel path length. In addition, the geometry of the system with the collimation along the path length and other absorbers off the path length should reduce the effect of photons being scattered back into the detector following an initial interaction in the path length. A detector "window" design was not used primarily because of possible alignment problems as the system is moved and temperatures vary in the bundle.

Assuming an exponential attenuation for the series arrangement of medians through which the beam passes, an expression may be written for the intensity at the detector;

$$I = I_o e^{-\mu_s \rho_s x_s} e^{-\mu \bar{\rho} x} , \tag{2}$$

where

I = intensity at the detector;
I_o = unattenuated intensity;
μ_s = mass absorption coefficient of wall material, cm²/g;
x_s = wall path length, cm;
μ = mass absorption coefficient of water, cm²/g;
x = subchannel path length, cm;
ρ_s = density of wall material, g/cm³;
$\bar{\rho}$ = average subchannel fluid density, g/cm³.

For an "empty" bundle with fluid density ρ_E this becomes

$$I_E = I_o e^{-\mu_s \rho_s x_s} e^{-\mu \rho_E x} . \tag{3}$$

The ratio of Eqs. (2) and (3) is

$$I/I_E = e^{-\mu x(\bar{\rho}-\rho_E)} , \tag{4}$$

which may be rewritten as

$$\bar{\rho} - \rho_E = \frac{1}{\mu x} \ln \frac{I_E}{I} . \tag{5}$$

In practice, each of the intensities in Eq. (5) is assumed to be related to the measured densitometer output voltage at the condition. The calibration equation is then

$$\bar{\rho} - \rho_E = K \ln \frac{V_E}{V} , \tag{6}$$

where

V_E = empty bundle output voltage,
V = measured voltage output,
K = constant determined from calibration.

The calibration points V_E and ρ_E are determined from an empty bundle or a high-quality steam data scan. A subcooled data scan provides the other endpoint necessary to determine a value for K.

For transient blowdown-type tests the calibration is straightforward. The preblowdown subcooled water properties and the postblowdown empty bundle provide fairly good calibration endpoints. Calibrations for steady-state tests are made using subcooled bundle data scans and high-quality or preferably superheated bundle data scans.

3. RESULTS AND DISCUSSION

The ion chambers were oven-tested prior to installation in the THTF bundle to characterize current leakage effects with temperature. Figure 7 shows the results of the oven tests. The ion chamber and ~2.43 m (8 ft) of the triax cable were heated. Leakage current is shown as a function of temperature for the two ion chambers DE-336U and DE-346L. The ion chambers did not meet the manufacturer's rated temperature of 613 K (644°F) without significant current leakage. The full-scale ionization-generated currents measured with the source and ion chamber installed in the THTF bundle are ~1 x 10^{-10} to 5 x 10^{-10} A, depending on actual axial location and bundle geometry. Significant errors will result as the leakage currents increase with temperature and approach the magnitude of the ionization-generated signal current. Sharp increases in leakage current are observed at ~589 K (600°F). The results for the DE-336U ion chamber during a heat-up and cooldown cycle also indicate significant hysteresis.

The densitometer system was installed in the THTF bundle in August 1980 and remained in the bundle for the transient Upflow Film-Boiling Tests 3.06.6B and 3.08.6C; the Steady-State Upflow Film-Boiling Test Series 3.07.9B X; the second series of Small-Break LOCA (SBLOCA) Tests, 3.09.10I-X; and the Intermediate-Flow Heat Transfer Tests 3.10.11A-H.

The design concept appears to work well for measuring the attenuation of the source across the subchannel. An easily measurable signal difference between a subcooled bundle and an empty bundle is observed at lower temperatures [less than ~560 K (550°F)]. Unfortunately, significant temperature problems occur at the temperatures of interest in terms of heat transfer data for the THTF tests.

As installed, the source-detector geometry results in an attenuation of the full-scale empty pipe signal to ~75% of that signal for a subcooled water-filled bundle. This agrees well with the theoretical exponential attenuation expected for the subchannel path length. The geometry apparently changes somewhat as the densitometer system is moved axially along the bundle. Figure 8 shows an example of a strip chart recording of the signal from the lower densitometer DE-346L during an axial traverse of the THTF bundle. The densitometers are moving up the bundle at ~50 cm/min (20 in./min). The test section contains subcooled water at ~366 K (200°F) and 4100 kPa (600 psi). The large peaks observed are the bundle spacer grids that are axially spaced ~61 cm (24 in.) apart. The variation in signals between the spacer grids indicates that geometry variations exist axially along the bundle. However, it does not necessarily indicate that the bundle has large variations in rod geometry, because relatively small displacements of the FRSs or instrument rods may cause significant changes in the source-detector geometry. These results indicate that in-place calibration is necessary at axial levels where measurements are desired.

The first in-bundle test results were obtained during the transient Upflow Film-Boiling Test 3.06.6B. The densitometers were positioned at primary FRS thermocouple levels E and F, which are located ~1.22 and 0.61 m (4 and 2 ft) below the upper end of the bundle heated length, respectively. The measurement signals are shown in Figs. 9 and 10.

For comparison of trends during the transient, the measurements from a densitometer located on an instrumented "spool piece" at the test section outlet are shown in Fig. 11. The outlet spool-piece densitometer is

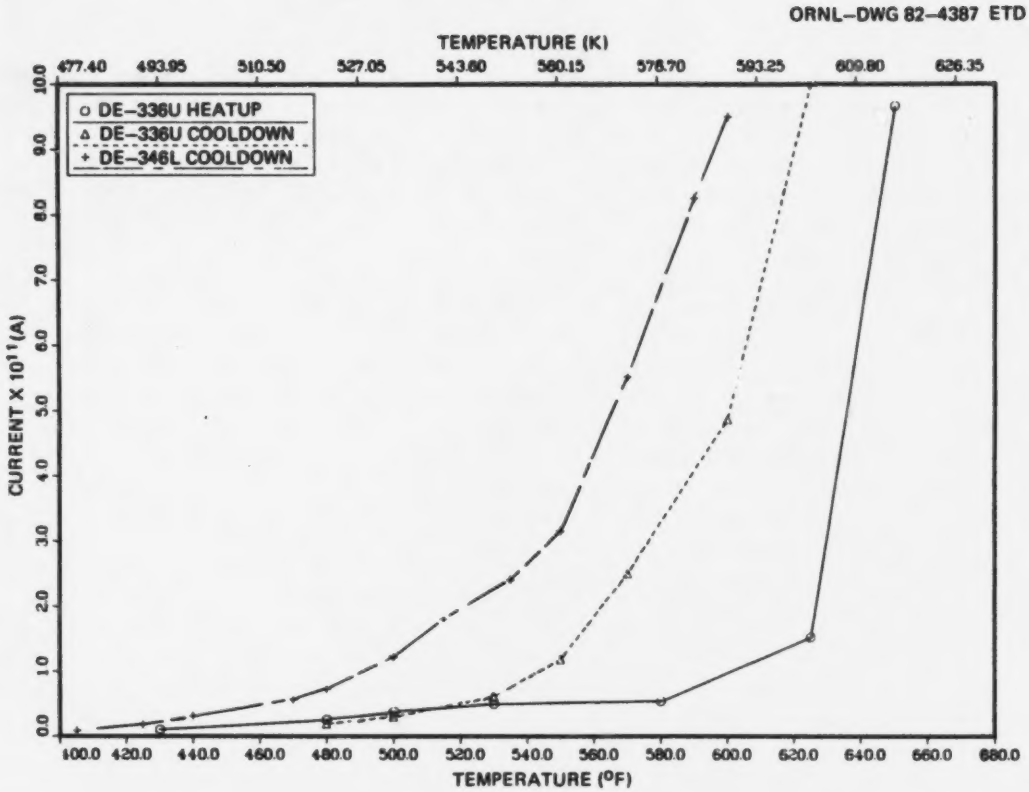

Fig. 7. Oven tests of in-bundle densitometer ion chambers.

a fairly reliable and proven design commonly used for average chordal density measurements in conduit. As such, for the unidirectional flow conditions of this test, it should provide a reasonable indication of conditions seen by the in-bundle densitometers. Results indicate temperature-effect problems at fluid temperatures above ~589 K (600°F). This agrees with results from the previously discussed oven-heating tests conducted in air prior to installation in the THTF bundle.

The in-bundle densitometers show the same trend and approximate densities as the spool-piece densitometer until ~3 s into the transient. From ~3 to 11 s into the transient, the in-bundle densitometers show apparently nonphysical behavior. The reason for this behavior seems to be temperature effect. Figure 12 shows both a plot of the fluid temperature measured at level F and the temperature measured inside the instrument rod in which the ion chamber is located. The latter temperature is measured by a thermocouple tack-welded onto the ion chamber guide tube ~7.6 cm (3 in.) above the ion chamber. The apparently nonphysical measurement made by the densitometer occurs at the same times as increases in the fluid temperature. The first gradual fluid temperature peak at ~4.5 s and the second sharper peak at ~10 s are mirrored by the in-bundle densitometer responses. As the fluid temperature decreases after ~11 s, the in-bundle densitometers show more reasonable trends. The temperature trace

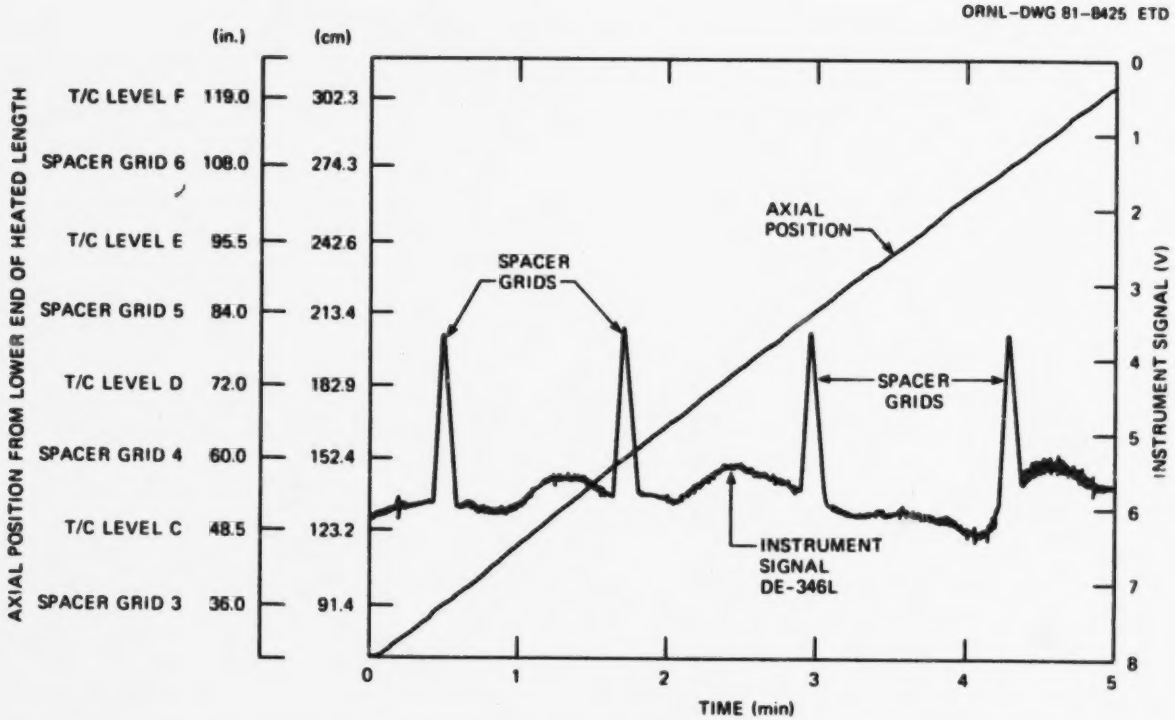

Fig. 8. Example of an axial traverse of densitometer up THTF bundle.

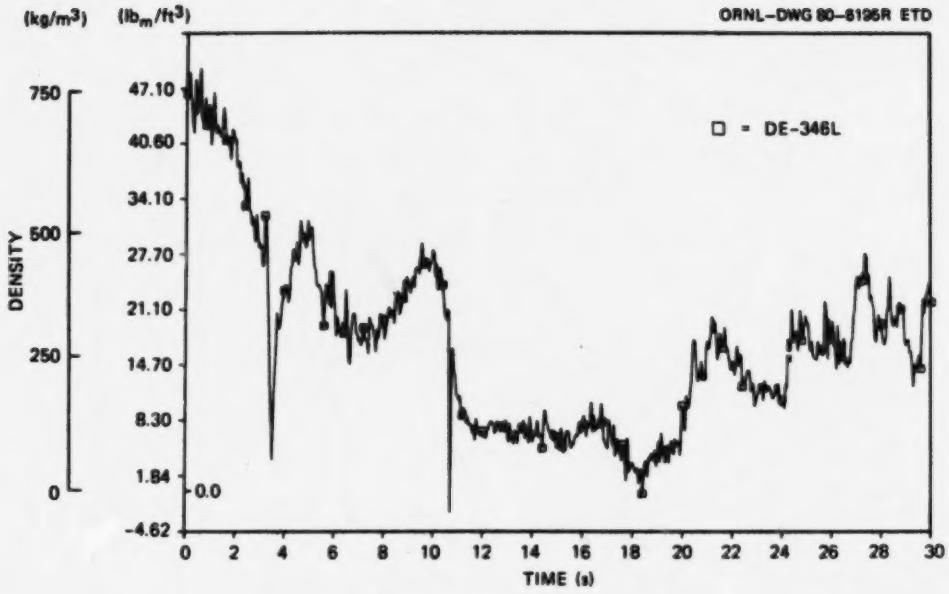

Fig. 9. In-bundle gamma densitometer density measurement at FRS thermocouple level E for test 3.06.6B.

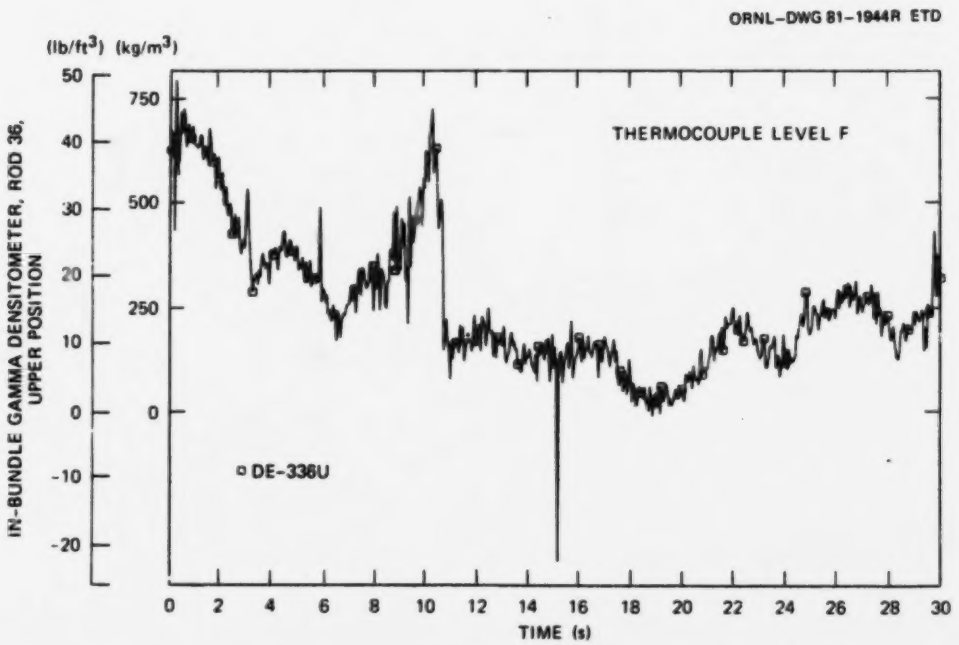

Fig. 10. In-bundle gamma densitometer measurement at thermocouple level F for test 3.06.6B (film boiling in upflow).

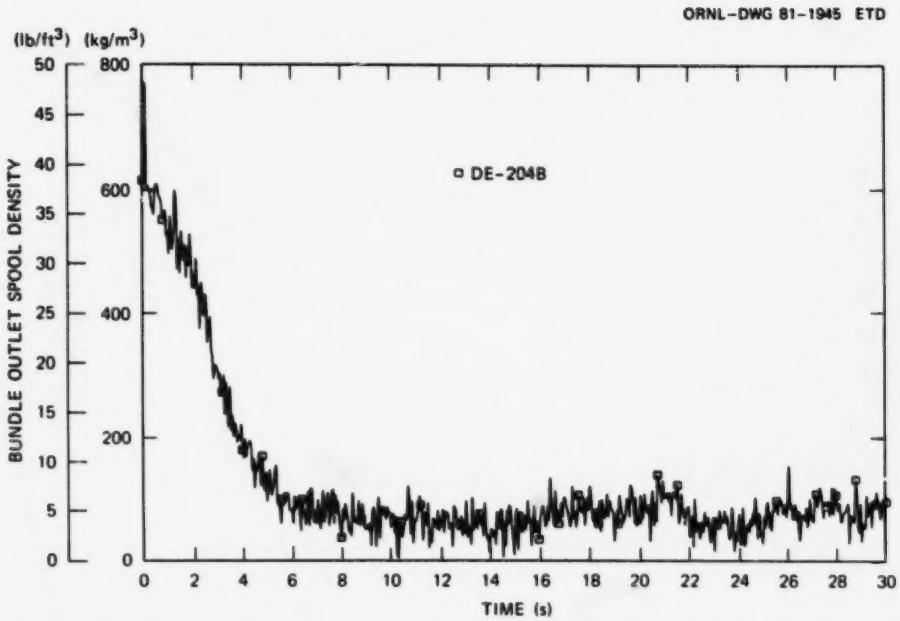

Fig. 11. Bundle outlet spool-piece gamma densitometer for test 3.06.6B (film boiling in upflow).

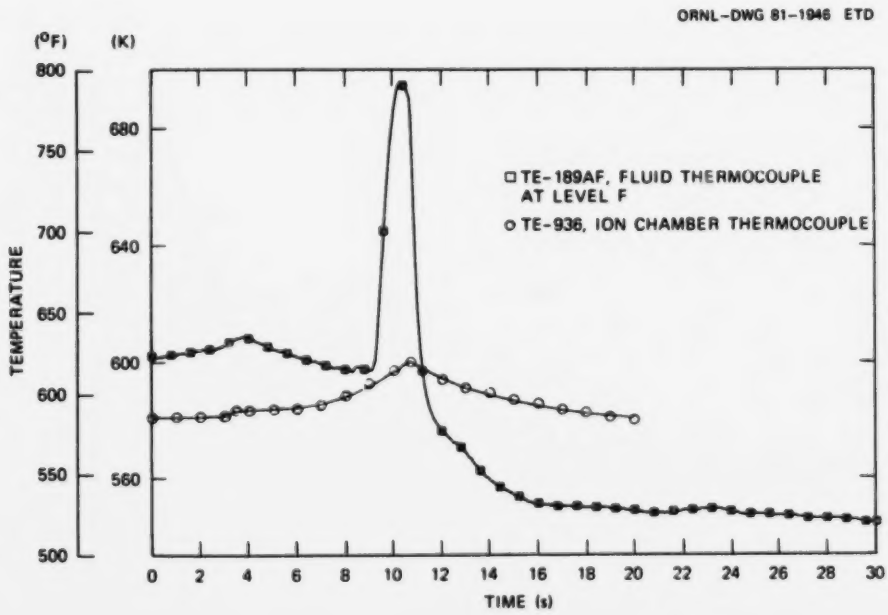

Fig. 12. Comparisons of fluid thermocouple and ion chamber thermocouple at thermocouple level F for test 3.06.6B (film boiling in upflow).

shown by the thermocouple tack-welded near the ion chamber shows somewhat the same trends as the fluid thermocouple temperature trace, although the former seems to be damped by the instrument rod wall and surrounding air.

The in-bundle densitometer actually follows the fluid thermocouple trend more closely than the thermocouple tack-welded near the ion chamber. This may indicate that the ion chamber has greater thermal contact with the instrument rod wall than with the thermocouple tacked near the ion chamber or possibly that geometry effects are causing the observed behavior.

The direction of the temperature effect is not as expected for current leakage from the signal wire. As the resistance of the insulators in the triax cable and ion chamber decreases with increasing temperature, the resulting current leakage would be expected to cause an increase in the measured current, thus decreasing the measured density shown in Figs. 9 and 10. Because the output current is very low (~5 x 10^{-10} A), it is possible that piezo-electric effects are producing the observed behavior. Temperature transients causing the materials of the triax cables to undergo differential thermal expansion may be producing piezo-electric effects.

As mentioned earlier, another possible explanation for the observed results may be rod geometry changes caused by high FRS or instrument rod temperatures. Small changes in rod position may produce significant changes in the subchannel geometry illuminated by the in-bundle densitometer. Observations during later tests showed that further increases in temperature caused a current swing in the direction expected for current leakage as a result of decreasing insulator resistance with temperature.

Similar results were obtained for the transient Upflow Film-Boiling Test 3.08.6C. Temperature effects again caused significant errors. Somewhat higher signal noise was also observed for this test than for test 3.06.6B. The in-bundle densitometer measurements are shown in Figs. 13 and 14. The measurement of density at the test section outlet is shown in Fig. 15 for comparison. Figure 16 shows the fluid temperature recorded at level F, where DE-336U was located. The in-bundle densitometer again mirrors the temperature trends for temperatures above ~589 K (600°F).

The effect of dc power applied to the bundle in which the ion chambers are located was also investigated. Observations during testing indicate that bundle power and changes in bundle power do not appear to have an observable effect on the ion chamber signal. A typical current measurement trace over the transient for one of the FRSs in the bundle is shown in Fig. 17. The fluid temperature will follow the bundle power to some extent. A comparison of Figs. 14, 16, and 17 indicates that the ion chamber is following the fluid temperature trends and not that of bundle power. The sharp drop in power (current) at ~21 s occurs after the fluid temperature and densitometer signal have already begun decreasing.

The Steady-State Upflow Film-Boiling Test Series 3.07.9 was run prior to test 3.08.6C. Useful data were not obtained because of calibration and high signal noise problems. The signal noise problems are again thought to be related to the temperature of the ion chamber or the triax cable. The reason for the calibration problems is not clear, although several possibilities exist. The data scans were taken at intervals over a fairly long operating time (longer than 10 h in some cases). Thermal cycles over this length of time in the rod bundle may be causing perturbations in the source-detector geometry. Because of the method of operation, subcooled

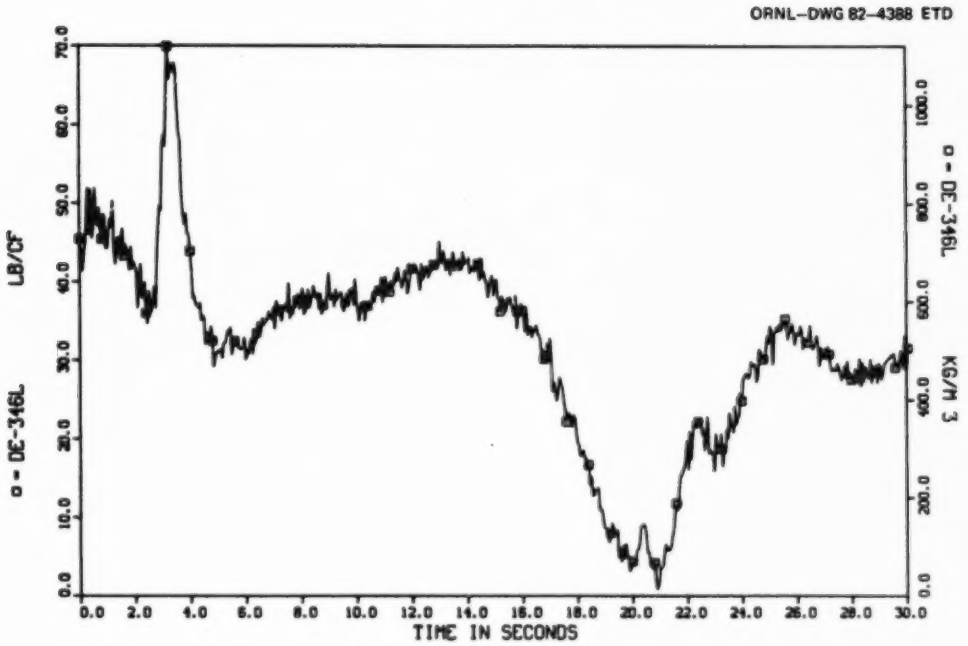

Fig. 13. In-bundle gamma densitometer measurement at thermocouple level E for test 3.08.6C.

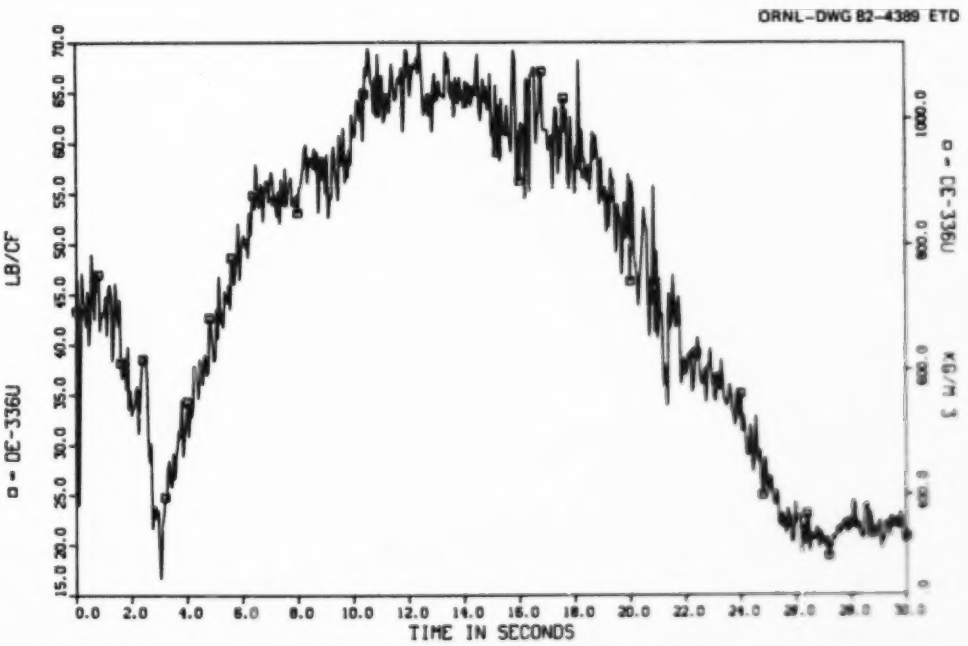

Fig. 14. In-bundle gamma densitometer measurement at thermocouple level F for test 3.08.6C.

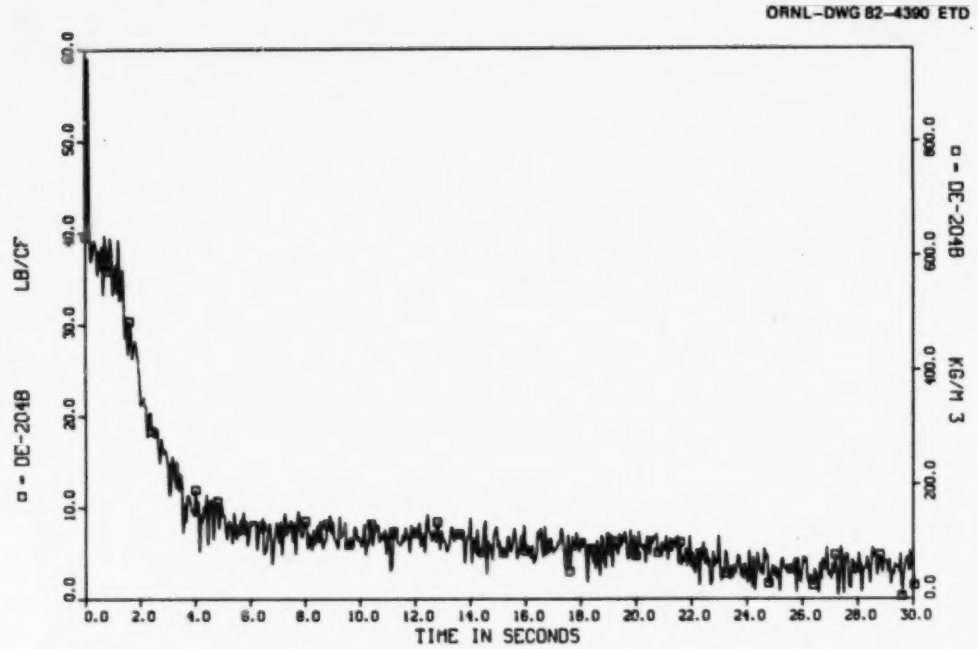

Fig. 15. Bundle outlet spool-piece gamma densitometer for test 3.08.6C.

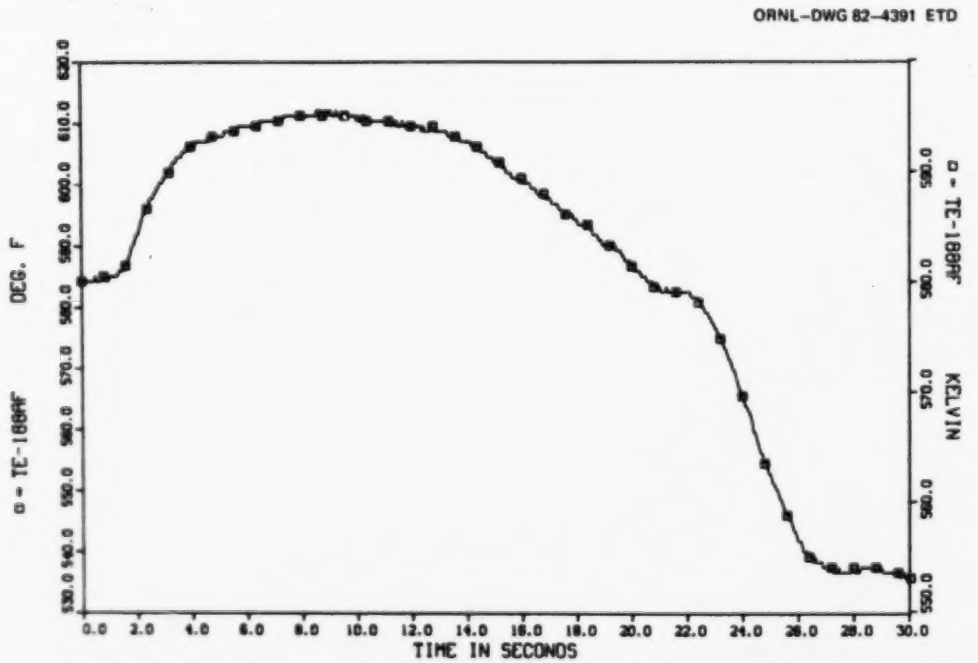

Fig. 16. Fluid thermocouple measurement at thermocouple level F for test 3.08.6C.

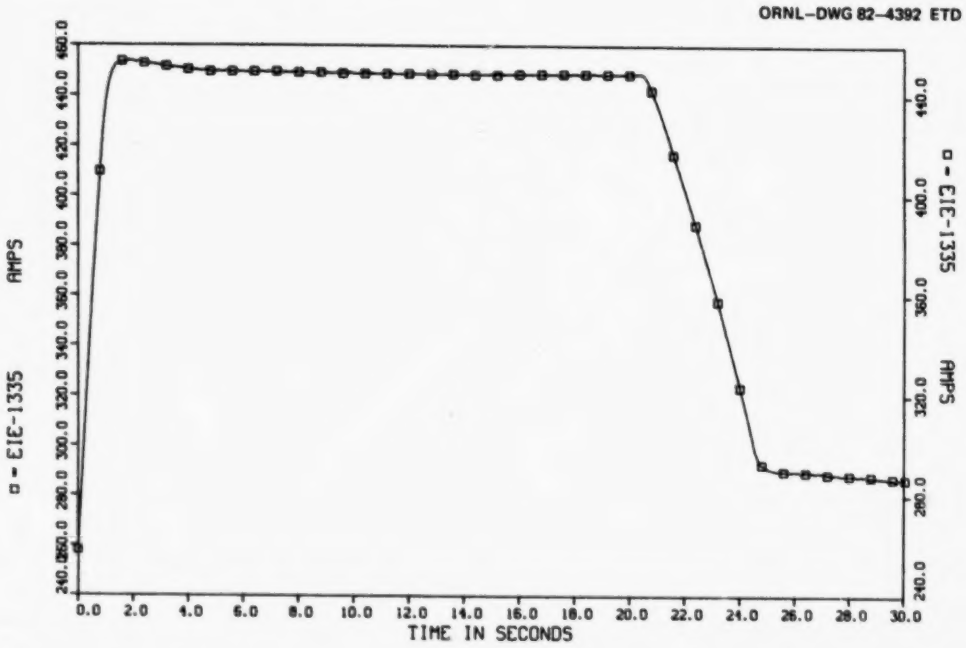

Fig. 17. Current measured in rod 35 for test 3.08.6C – typical of all heater rods in bundle.

scans that can provide one endpoint for the calibrations are not always available at times near the test data scans. The high-quality or superheated data scans that are the other endpoints for the calibration are of necessity taken when temperatures are fairly high and the ion chamber or triax cable may be experiencing temperature-effect problems.

The densitometer system remained in the bundle for the SBLOCA-II Test Series 3.09.10I-X and the Intermediate-Flow Heat Transfer Test Series 3.10.11A-H. Considerably higher fluid temperatures [755 to 866 K (900 to 1100°F)] were observed for these tests than for earlier ones. As expected from previous testing, temperature effects prevented any useful data from being obtained. High temperatures and thermal cycling also caused an apparent irreversible mechanical failure in one of the ion chambers. Resistance checks showed a low resistance between the center wire and outer sheath of the ion chamber, indicating a probable seal or insulator failure in the ion chamber.

4. SUMMARY AND CONCLUSIONS

The design concept appears to work well in measuring the attenuation of a source across subchannels of a rod bundle. An easily measurable signal difference between a subcooled bundle and an empty bundle is observed at low temperatures. Presumably because of the ion chamber and triax signal cable, the system suffered from high-temperature effects as fluid temperatures approached ~589 K (600°F). As a result, useful data on in-bundle void fraction during THTF tests were not obtained.

Calibration of the densitometers was fairly straightforward for the transient THTF tests where preblowdown and postblowdown conditions provided well-defined endpoints. Calibration difficulties were encountered for steady-state tests where long times between calibration points and data scans as well as high-temperature effects on the low-density calibration endpoints caused problems. Possible variation in the source-detector geometry over long periods of time because of high FRS temperatures and thermal cycling may also have contributed to the calibration problems.

Results from the transient tests indicate that dc bundle power and changes in bundle power apparently do not affect the ion chamber signal.

Although useful data were not obtained during the THTF tests because of high-temperature effects, application of the design concept to rod and tube bundles operated at lower temperatures may provide a useful in-bundle measurement system. Improvements in the ion chamber and triax cable temperature capabilities, such as employment of a fully guarded ion chamber, may extend the useful range of the system. It is doubtful, however, that improvement in temperature capabilities to the 755 to 866 K (900 to 1100°F) fluid temperatures observed in the THTF SBLOCA test series is feasible in the near term.

Because the in-bundle densitometer concept is a noninterference measurement system, it may also have application as a local in-bundle standard for evaluating interference-type liquid level and void probes. An in-bundle densitometer illuminating the subchannel region in which another probe is located may provide considerable insight into the observed responses of the probe.

Finally, although not feasible in the THTF, a detailed study of the effect of such parameters as quality, pressure, and flow regime in a lower-temperature bundle is recommended to better characterize the subchannel design concept response to two-phase flow.

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